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The qualification of torrefied wooden biomass and agricultural wastes products for gasification processes

S. Arnsfeld*, D. Senk, H.-W. Gudenau

Department of Ferrous Metallurgy, RWTH Aachen University, D-52056 Aachen, Germany

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ABSTRACT

The present work is focused on the characterization of torrefied biomass and their application for (fast) gasification purposes. Since the upscaling of the torrefaction process from laboratory scale to commercially pilot plants is not fully understood, laboratory results do not reflect the characteristics of commercially available torrefied products gained from theses plants.

A step toward bridging this gap lies in a general evaluation of commercially available torrefied products, which should be independent from the preceding processing conditions and which focuses on the specific requirements of the product's technical application.

In this spirit, this work focuses on different torrefied products and torrefaction degrees examined with selected, common characterization methods. The influence of the torrefaction process on surface characteristics, especially the development of the porous structure, is investigated. The torrefied material is evaluated in terms of its process temperature management via combined thermogravimetric and differential scanning calorimetric analysis. Since empiric predictions based on fossil coals do not match the characteristics of torrefied material, common analytical methods for fossil coals like ultimate and proximate analysis are also discussed.

The methodology laid out in this work enables the user to establish a pre-selection of the torrefied biomass type and the torrefaction temperature for its further application in industrial fast gasification processes.

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1. Introduction

To increase sustainability huge carbon-based industries like chemical industry, power industry or steel industry, investigations are carried out to substitute carbon from fossil origins like oil or coal by biomass. In general, the biomass is transformed into gaseous products via different elevated temperature routes. The major route is gasification or combustion under high temperatures in an oxidative atmosphere [1–4].

For combustion purposes the burnout rate of each particle must be close to the maximum, so the residual ash contains no carbon at best. In combustion processes, temperature and oxygen concentration of the atmosphere leads to high efficiency of the carbon containing fuel.

For gasification purposes the oxygen concentration in the atmosphere is reduced, which leads to lower burnout rates than for combustion. A fast gasification requires fast reaction kinetics and therefore demands a careful preparation of the carbon containing fuel [5].

Raw biomass contains large amounts of water, which has to be removed to increase the specific heating values. One of the most popular biomass substitutes, if raw biomass cannot be used, is charcoal. But the solid yield of charcoal after production is only around 33% of the original dry, wooden biomass. The torrefaction process, a mild pyrolysis at lower temperatures, results in solid yield of over 70%, which might be of interest for a sustainable use of biomass [6–9].

Due to the massive weight loss of biomass at temperatures up to 350 °C, the production of torrefied biomass with defined characteristics for gasification like specific caloric values, concentration of carbon in solid residue is difficult to achieve [10,11]. Furthermore, no universal criteria for biomass prepared for gasification is existing, but some proposals have been given to evaluate the

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Abbreviations: BET method, Brunauer–Emmett–Teller method; DSC, differential scanning calorimetry; LOM, light optical microscopy; MIP, mercury intrusion porosimetry; PCI, pulverized coal for combustion; TBM, torrefied biomass; TGA, thermogravimetric analysis.

* Corresponding author. Tel.: +49 711 459 24701; fax: +49 711 459 24702.
E-mail address: arnsfeld@uni-hohenheim.de (S. Arnsfeld).

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torrefaction degree [12]. For fossil coals, the amount of volatile matter and fixed carbon in combination with the specific heating values allows a general conception of the gasification abilities of each coal type [13–15]. These values do not match the product characteristics of torrefied materials. An evaluation of torrefied products for fast gasification purposes is not possible, yet. Experimental results from laboratory scale vary from those gained from pilot plants. The torrefaction process itself varies according to the utilized reactor type and further complicating matters. Right now, commercially available torrefied material cannot be evaluated for industrial application.

In this investigation the characteristics of different types of torrefied biomass, especially at high torrefaction temperatures around 300 °C, are presented and evaluated. The torrefaction reactor is a pilot plant (laboratory torbed reactor); its product similar to commercially available torrefied material. Since the torrefaction process defines product quality of its solid residues and therefore its gasification characteristics, a characterization of the torrefied material in comparison to fossil coals is crucial for its further technical application in fast gasification processes.

2. The torrefaction process

The torrefaction process is a mild pyrolysis process at temperatures 200–350 °C. The raw biomass is heated to evaporate the moisture at the initial stage. It loses physically bonded water during the second stage and is heated up to 200 °C slowly. Then the main torrefaction process starts with low heating rates around 10 K/min and the release of volatiles until the torrefaction temperature is reached. After torrefaction time, the product is quenched in order to conserve the solid yield. Due to the post-combustion of volatiles, released during torrefaction process, the process can be run and therefore defined as autotherm.

During the torrefaction process molecular bonded water is released (in combination with carbon dioxide). In contradiction to charcoal the torrefacting biomass does not undergo a molecular reorganization of its structure. Its ignition temperatures in air atmosphere are lower than those of charcoal due to the faster reaction kinetics of the original molecular structure. The specific heating values of the solid products are higher than of raw biomass due to the loss of water during torrefaction process [16].

The torrefied product must be characterized independently from its former torrefaction process to exclude both scaling effects and influences of different reactor types. As mentioned before, common criteria for fossil coals do not match the product characteristics of torrefied materials. Therefore this paper aims to present some characterization methods and its information concerning the general applicability of torrefied biomass for fast gasification purposes.

3. Materials

Two different wood types which are common in European countries were chosen:

- Softwood: Pine wood.
- Hardwood: Beech wood.

The wood samples were, without bark and already chipped, torrefied at three different maximum temperatures to get samples from all temperature levels of the torrefaction process:

- Low: around 220 °C.
- Medium: around 250 °C.
- High: around 300 °C.

Since the interest in biomass has increased during the last years, the prices for wood increased as well. So, three different agricultural wastes were chosen to compare the influence of the torrefaction process on wooden biomass and agricultural wastes. According to the results from the two wood types only high torrefaction temperatures are suitable for fast gasification purposes as the results will point out.

There is a broad variety among agricultural wastes. For gasification purposes this investigation concentrates on hard agricultural wastes like shells.

- Palm kernel shells
- Pine kernel shells
- Almond shells

All biomasses were torrefied under the same process conditions (heating rate and torrefaction time) in a laboratory torbed reactor [17,18]. Proper preparation of the raw material concerning water content, particle size and geometry is crucial for a proper heat transfer inside the reactor for a homogeneous torrefied product. The same is valid for the torrefaction process itself: The heating rate and the torrefaction time must be followed in a small range due to the fast reaction kinetics especially at high torrefaction temperatures. In the case of almond shells, they have been crushed, the other two types of shells were transported through the reactor in whole size. The torrefied products were crushed and milled. It must be stated, that the results of the elementary and proximate analysis depend strongly on the reactor type and its conditions and cannot be simulated by upscaling from laboratory results due to different heat transfer conditions. Recently Aziz et al. have presented their laboratory results on palm kernel shells in [19]. The pilot plant experiments were carried out at the GWI in Essen in cooperation with RWE Innogy. The task at the department of ferrous metallurgy was to evaluate the torrefied product for application in ironmaking processes.

Therefore, in comparison to the results of the ultimate and proximate analysis of the torrefied materials, two additional materials were investigated:

- A commercially available Softwood** (type not specified), heat pre-treatment in absence of oxygen at temperatures between 340 and 400 °C.
- A commercially available charcoal (from beech wood), pyrolyzed between 500 and 600 °C.

**: Material provided by Münch Edelstahl GmbH, Hilden, Germany.

4. Methods

The residual samples according to Table 1 were analyzed using light microscopy analysis, ultimate and proximate analysis after

Table 1
Investigated torrefied samples from different types of biomass.

Biomass	Sample No.	Temperature level		
		Low	Medium	High
Pine wood	1	×	×	×
Beech wood	2	×	×	×
Palm kernel shells	3	–	×	×
Pine kernel shells	4	–	–	×
Almond shells	5	–	–	×

Table 2
Ultimate analysis of torrefied wooden biomass.

Type of biomass	Temperature level	C (wt.%)	H (wt.%)	N (wt.%)	Ash (wt.%)	O (wt.%)	Atomic ratio O/C	Atomic ratio H/C
Pine wood	Low	50.4	6.28	0.13	0.41	42.8	0.64	1.50
Pine wood	Medium	50.4	6.29	0.12	0.70	42.5	0.63	1.50
Pine wood	High	53.4	6.04	0.14	0.66	39.8	0.56	1.36
Softwood	340–400 °C	63.9	5.59	0.14	0.98	29.4	0.35	1.05
Fossil coal (PCI-1)	Raw	81.6	4.18	1.62	9.03	3.6	0.03	0.61
Charcoal	500–600 °C	84.0	2.93	0.58	2.38	10.1	0.09	0.42
Beech wood[a]	Raw	49.4	6.21	0.05	0.43	43.9	0.67	1.51
Beech wood	Low	52.0	5.57	0.20	0.47	41.8	0.60	1.29
Beech wood	Medium	52.2	5.54	0.21	0.48	41.6	0.60	1.27
Beech wood	High	56.1	5.33	0.23	0.60	37.7	0.50	1.13

[a] Data from LEAT Bochum.

Table 3
Ultimate analysis of torrefied shells.

Type of biomass	Temperature Level	C wt.-%	H wt.-%	N wt.-%	Ash wt.-%	O wt.-%	Atomic ratio O/C	Atomic ratio H/C
Palm kernel shells[a]	Raw	53.9	6.24	0.37	2.17	37.3	0.52	1.39
Palm kernel shells	Medium	61.3	5.46	0.56	2.27	30.4	0.37	1.07
Palm kernel shells	High	62.9	5.21	0.54	2.50	28.9	0.34	0.99
Pine kernel shells[a]	Raw	46.9	5.89	0.48	1.28	45.5	0.73	1.51
Pine kernel shells	High	59.8	5.26	0.21	2.54	32.2	0.40	1.06
Almond shells[a]	Raw	50.8	5.84	0.46	1.35	41.6	0.61	1.38
Almond shells	High	60.9	5.14	0.20	1.36	32.4	0.40	1.01

[a] Data from LEAT Bochum.

DIN 51718–DIN 51722, DIN51732, DIN 51734 and DIN 51900-1. The amount of oxygen was calculated via Eq. (1).

$$\%[O] = 100\% - \%[Ash] - \%[C] - \%[H] - \%[N] \quad (1)$$

Investigations of the surface and the porosity were carried out using BET method and MIP (Mercury Intrusion Porosimetry). For BET, all samples were milled and sieved to achieve particle diameters between 90 and 125 microns. For MIP, all samples remained in their original, coarsely milled state. Unlike BET an analysis of the whole surface area is not under investigation. But the MIP method (ASTM D 4404) allows obtaining the complete porosity of a material and the distribution of the porous volume in comparison to the diameter of a pore. Since biomass provides false responses due to its elasticity at higher mercury pressures, the investigated diameter range was >1 micron. In that case, the maximum mercury pressure was similar to ambient pressure and false responses can be excluded.

Investigations to characterize the torrefaction state of torrefied materials were carried out using a TGA/DTG Analysis and DSC. A SETSYS Model Evolution 1750 thermogravimetric analyser was used to continuously monitor weight changes in different samples due to drying, pyrolysis, volatilization and gasification as the sample followed the linear heating program. At 200 °C the temperature was hold for 10 min for drying. The instrument provided the continuously recording DTG and DSC curves, in terms of weight loss rate (in wt.-%/min) and heat flow (in mW) which could be converted as per calibration chart to obtain heat flow per initial mass unit (mW/mg). The argon gas flow rate was maintained at 20 ml/min, the heating rate was maintained at 10 K/min. The initial weight of the samples was 13 mg.

With the DTA a combined TGA/DTG with DSC analysis it is possible to evaluate whether the torrefaction process is close to its autotherm limits or can be run autotherm at higher torrefaction temperatures. This depends on whether the DSC shows endo- or exothermic reactions.

5. Results and discussion

5.1. Proximate and ultimate analysis

Biomass is composed of carbon, hydrogen and oxygen. Wooden biomass consists of three different organic compounds: lignin, cellulose and hemicellulose. All three components have large amounts of oxygen bonded in hydroxyl groups to the skeletal main molecule. These groups decompose when the material is heated, forming oxygen-containing carboxylic acids, especially formic acid and acetic acid, which decompose to water and carbon dioxide at further elevated temperatures [16,20].

Table 4
Proximate analysis of torrefied wooden biomass.

Type of biomass	Temperature Level	C_{fix} (wt.%)	VM (wt.%)	LHV (MJ/kg)	HHV (MJ/kg)
Pine wood	Low	14.5	84.7	18.93	20.30
Pine wood	Medium	16.8	80.2	19.23	20.60
Pine wood	High	20.8	76.2	19.94	21.25
Softwood	<400 °C	48.2	45.0	23.73	24.93
Fossil coal	Raw	66.5	24.6	29.81	30.80
Charcoal	>500 °C, coked	78.3	18.3	29.92	30.56
Beech wood[a]	Raw	–	85.1	18.16	–
Beech wood[a]	Low	–	82.0	17.29	–
Beech wood[a]	Medium	–	80.0	18.16	–
Beech wood	High	19.9	68.6	19.92	21.08

[a] Data from LEAT Bochum.

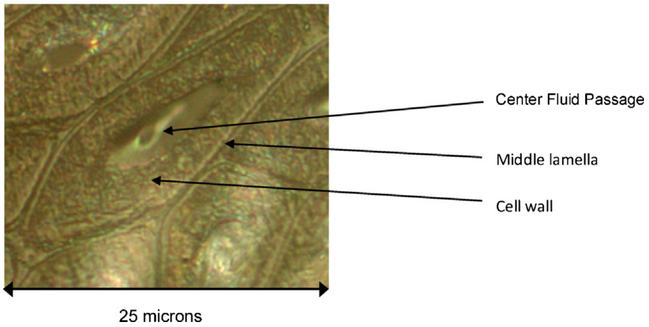

Fig. 1. Beech Wood (Raw), LOM.

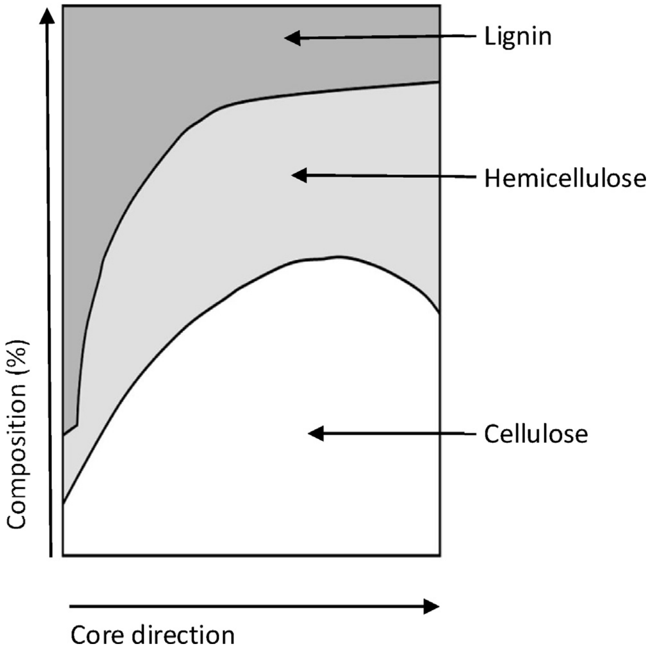

Fig. 2. Sketch of composition of cellulose, hemicellulose and lignin [21].

Compared to fossil coal (PCI-1), Table 2, which is used as pulverized injected coal in blast furnaces today, torrefied biomass has negligible amounts of ash, but higher amounts of oxygen. With lower and medium pyrolysis temperatures changes of the elementary composition cannot be detected. At higher pyrolysis temperatures the carbon concentration increases and specifically the oxygen concentration of the solid product decreases.

Agricultural wastes like shells have higher ash concentration than wooden biomass, but lower than for common fossil coals according to Tables 2 and 3. The amount of oxygen is lower after torrefaction process than of wooden biomass, but this is due to lower oxygen content of the original material and not of the torrefaction process itself.

It seems that wooden biomass needs higher torrefaction temperatures to achieve similar compositions than the different shells. In both cases, the achieved values after torrefaction process strongly depend on the origin of the material. The difference between softwood and hardwood is not large in comparison to the shells (Table 4).

Both wooden biomass types show similar values of proximate analysis, despite the analyzed hardwood (beech wood) shows lower amounts of volatile matter after high torrefaction temperature. From ultimate analysis one could assume, that the fixed carbon content and heating values of shells should be similar to softwood (<400 °C). But the opposite is true: Despite their similar elementary composition, the fixed carbon content of all investigated shells is significantly lower than for softwood (<400 °C), the amount of volatiles is higher for each shell type than for softwood (<400 °C). Since the torrefaction process was the same for all 'high' torrefied samples, this indicates different torrefaction behavior for wooden biomass and shells followed by different (fast) gasification characteristics for the torrefied product. The combination of different (fast) gasification characteristics with same elementary composition must result in a crucial role of molecular structure in gasification kinetics (Table 5).

Every biomass showed lower heating values than the fossil coal. The values of the fossil coal could not be achieved through torrefaction process. But from Table 3, it is known, that charcoal, pyrolyzed at higher temperatures (>500 °C) can show similar values for both proximate and ultimate analysis compared to fossil coals.

5.2. Light optical microscopy

Figures 1–5 show the difference of softwood (pine) and hardwood (beech). Softwood has a fine porous structure, while hardwood contains less, but bigger pores.

In the temperature range of the torrefaction process mainly the degradation of hemicellulose and lignin takes place. Cellulose does not start degradation at temperatures lower than 320 °C according to [20]. The microstructure of raw beech wood is presented in Fig. 1; the composition of cellulose, hemicellulose and lignin is shown in Fig. 2.

Due to the degradation of hemicellulose the pores from the center fluid passage are growing. The degradation level depends on torrefaction temperature level (Figs. 3.1–5.1, Figs. 3.2–5.2). The decomposition of hemicellulose leads also to less mechanical

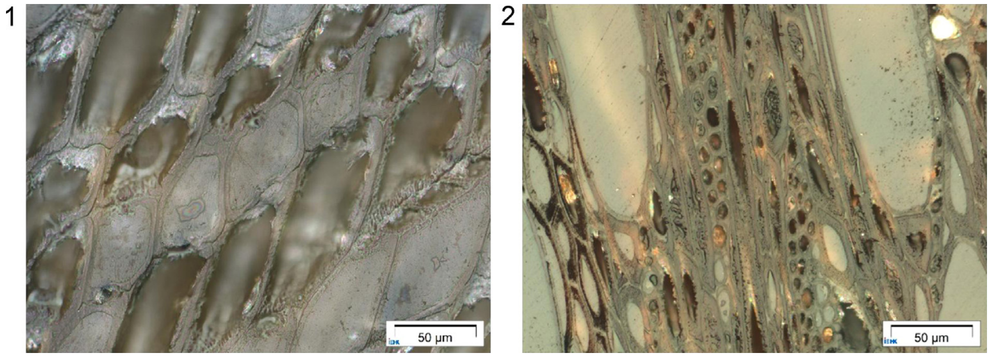

Fig. 3. (1) Pine wood (Low). (2) Beech wood (Low).

Table 5
Proximate analysis of torrefied shells.

Type of biomass	Temperature level	C_{fix} (wt.%)	VM (wt.%)	LHV (MJ/kg)	HHV (MJ/kg)
Palm kernel shells[a]	Raw	–	77.7	21.47	–
Palm kernel shells	Medium	30.9	65.8	23.18	24.37
Palm kernel shells	High	35.9	60.2	22.93	24.06
Pine kernel shells[a]	Raw	–	77.2	19.40	–
Pine kernel shells	High	33.0	63.0	23.06	24.20
Almond shells[a]	Raw	–	79.9	18.39	–
Almond shells	High	38.1	59.2	23.30	24.45

[a] Data from LEAT Bochum.

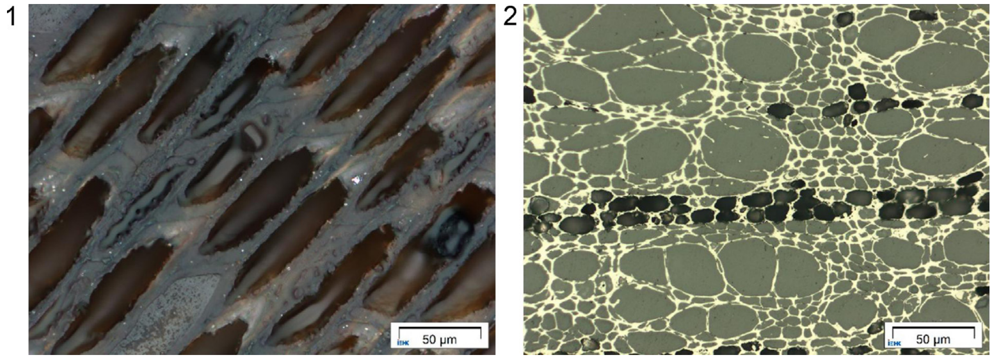

Fig. 4. (1) Pine wood (Medium). (2) Beech wood (Medium).

stability at 'high' pyrolysis temperatures, resulting in better values for grindability [22,23].

The three types of shells (Figs. 6.1, 6.2, 7.1 and 7.2) show a fine porous structure, each unique for the shell type.

The characteristic structure of the original biomass remains intact after torrefaction process. Differences of porous structures as a result of the torrefaction process are not detectable via light optical microscopy.

In general, the surface area of torrefied biomass and fossil coal can be considered as comparable, since the difference to fossil coals are just between 30 and 40%. Coke and especially charcoal have significantly larger specific surfaces, shown in Table 6.

Table 6
BET analysis of different samples.

Material	Temperature level	BET (m^2/g)
Fossil coal	Raw	2.31
Pine wood	High	1.63
Beech wood	High	1.40
Palm kernel shells	High	–
Pine kernel shells	High	1.37
Almond shells	High	1.70
Coke (for blast furnaces)	Coked	3.36
Charcoal	Coked	59.57

5.3. *Mercury intrusion porosimetry (MIP)*

The results for the porosity, gained from MIP measurements, are presented in Table 7. The porosity of each biomass is increasing with the torrefaction temperature, whereas the skeletal density shows no direct congruency with torrefaction temperature at all.

The pore size distribution in Fig. 8 shows significant differences between shells and wooden biomasses: Shells have smaller pores and a finer porous structure similar to pulverized fossil coals for injection, whereas wooden biomass shows a unique structure for each respective type.

Two different kinds of developing pores, shown in Fig. 9, can be detected: These pores (around 25 microns pore diameter at low torrefaction temperature) increase with increasing torrefaction temperature to a diameter range between 50 and 100 microns, doubling the incremental pore volume from 'medium' to 'high' pyrolysis temperature.

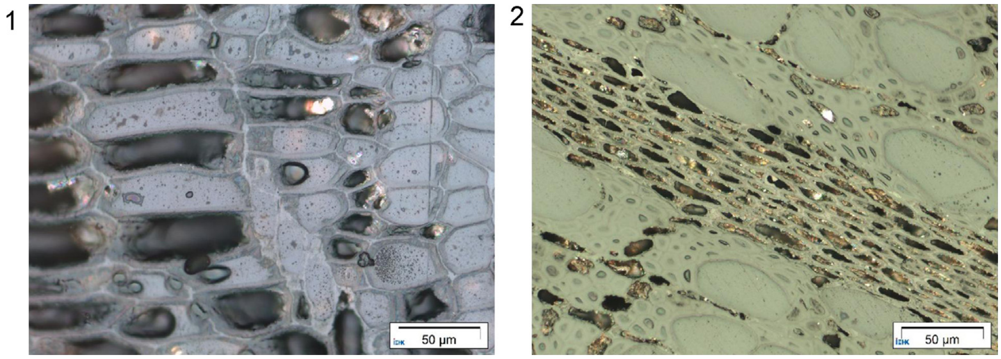

Fig. 5. (1) Pine wood (High). (2) Beech wood (High).

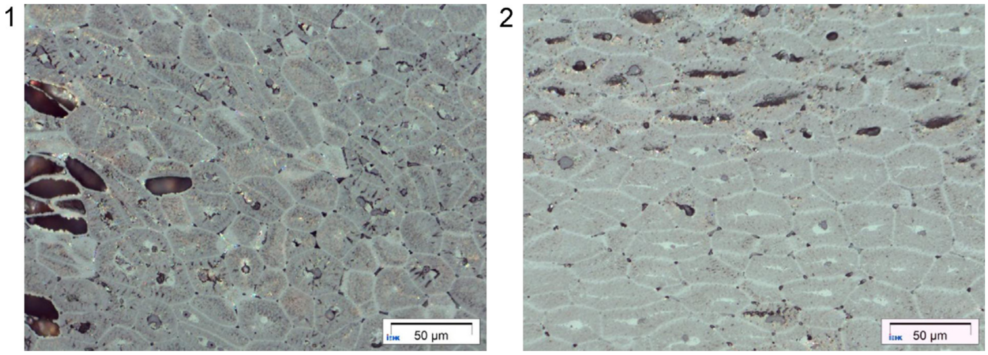

Fig. 6. (1) Palm kernel shells **(**Medium). (2) Palm kernel shells (High).

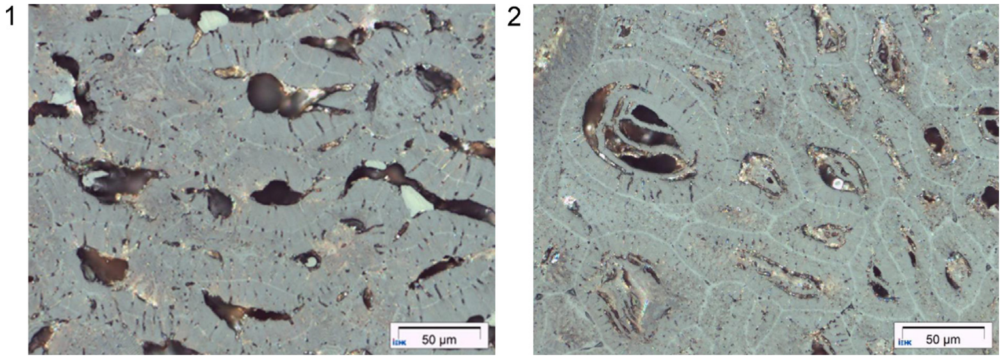

Fig. 7. (1) Pine kernel shells (High). (2) almond shells (High).

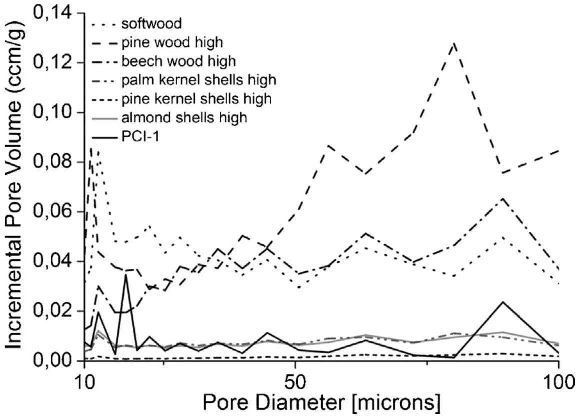

Fig. 8. Pore size distribution of all biomasses, torrefaction temperature level 'high'.

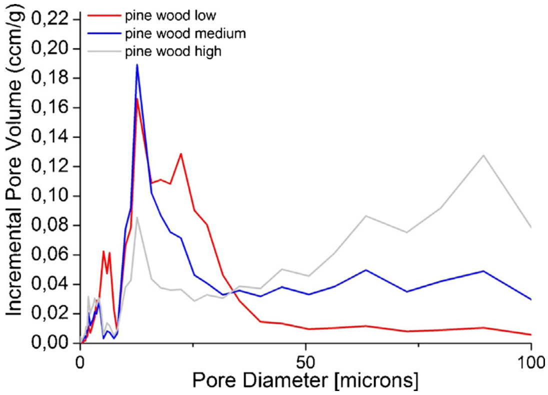

Fig. 9. Pore size distribution of pine wood at different torrefaction temperature levels.

Table 7
MIP results of different samples.

Material	Temperature level	Apparent (skeletal) density (g/cm^3)	Porosity (vol.%)
Pine wood	Raw	1.424	67.6
Pine wood	Low	1.085	63.5
Pine wood	Medium	1.021	67.1
Pine wood	High	1.219	73.3
Softwood	<400 °C	1.338	65.8
Beech wood	Raw	1.463	47.9
Beech wood	Low	1.359	64.5
Beech wood	Medium	1.446	66.0
Beech wood	High	1.394	71.3
Palm kernel shells	Medium	1.436	27.6
Palm kernel shells	High	1.395	32.3
Pine kernel shells	High	1.475	28.7
Almond shells	High	1.418	44.1
Pulverized coal	Raw	1.302	48.7

Smaller pores with pore diameter <10 microns at low pyrolysis temperature increase with increasing temperature to a diameter range up to 20 microns at 'medium' pyrolysis temperature. These pores may coalesce into bigger pores at 'high' pyrolysis temperature.

For beech wood the development of the porous structure is more inhomogeneous (Fig. 10) than for pine wood. With beginning of the torrefaction process pores are growing up to 10 microns, at medium temperatures pore sizes between 13 and 25 microns occur. In contradiction to the results of pine wood, there is no evidence for these pores growing from specific smaller pores. High torrefaction temperatures improve the growth of bigger pores (>25 microns) from smaller ones. This coalescing part at high torrefaction temperatures is similar to the coalescing part above 25 microns for pine wood.

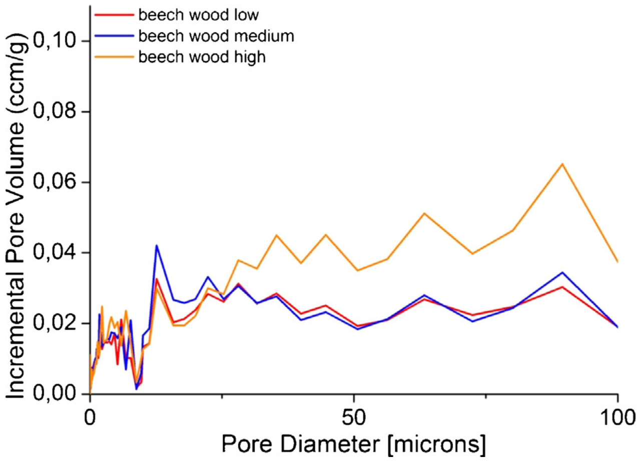

Fig. 10. Pore size distribution of beech wood at different torrefaction temperature levels.

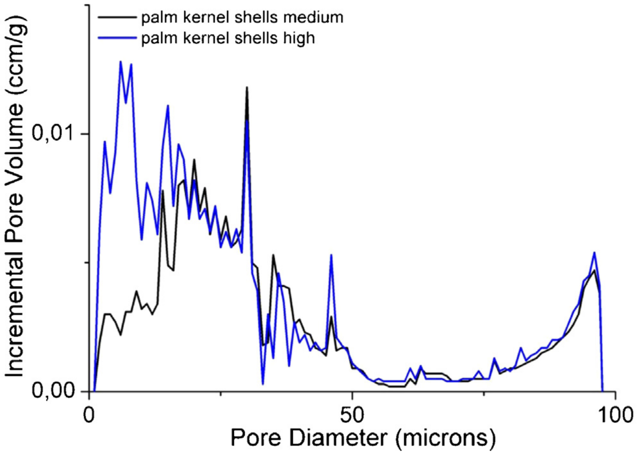

Fig. 11. Pore size distribution of kernel shells at torrefaction temperature levels 'medium' and 'high'.

For palm kernel shells, a specific growth of smaller pores can be detected in Fig. 11 between 15 and 17 microns. The increase of porosity of the shells during torrefaction process is done by the appearance of small pores up to 12 microns. In general, the increase of porosity of shells is much smaller than for wooden biomass.

5.4. *Differential thermogravimetric analysis of pyrolysis behavior after torrefaction process at elevated temperatures*

The thermogravimetric results in Fig. 12.1 and 2 show three different stages of degradation of biomass:

- Drying stage: Loss of water
- Devolatilizing stage: Fast loss of parts of volatile matter
- Pyrolysation stage: When polymerization reactions are activated, the massive loss of volatile matter due to cracking reactions slows down.

For the two investigated types of wood, beech wood (hardwood) and pine wood (softwood), both torrefied at high temperatures, the final mass loss at 800 °C is close to the initial content of volatile matter. The massive weight loss slows down around 300 °C (pine wood) and 360 °C (beech wood) with around 70% of the final weight loss at 800 °C. For the pyrolyzed wood (softwood) the final mass loss was higher than the initial content of volatile matter, indicating that the polymerization reactions must have started a transformation of the molecular structure, releasing additional mass. Since the massive weight loss ended at around 300 °C with lower losses than for both, pine and beech wood, the dominating devolatilisation process must have changed into a dominating polymerization process during pyrolysis with release of the gaseous fraction.

For the three investigated agricultural wastes, palm kernel shells, pine kernel shells and almond shells the final mass loss at 800 °C is close to the initial content of volatile matter. But the massive weight loss stops at around 50% of the final weight loss at 800 °C, the slowdown temperature for all three shell types is 350 °C, which is in case of almond shells close to the original (non-torrefied) state [24].

The results from the differential scanning calorimetry in Fig. 13.1 and 2 should show a characteristic peak <200 °C due to the release of water. Due to the different impact of the drying stage on the materials, this part of the experiment is not shown. It is lower for the shells than for wood due to the smaller water content of the shells.

The level of the heat flow with palm kernel shells and pine kernel shells were similar, whereas the signal for the pine shells was significantly lower for the whole temperature range. Especially both investigated softwoods show higher exothermic heat flows than beech wood, despite their different process temperatures. This is a clear sign for the general potential to increase torrefaction temperatures in an autothermic torrefaction process mode. Beech wood does not show this clear signal, an increase of the torrefaction with autothermic process conditions might be possible nonetheless.

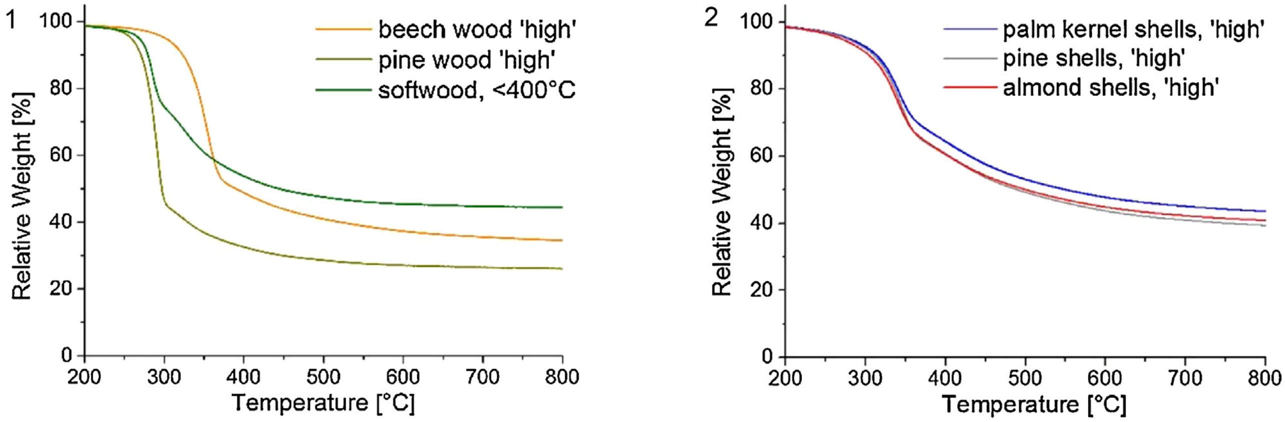

Fig. 12. (1) TGA curve of woods (High). (2) TGA curve of shells (High).

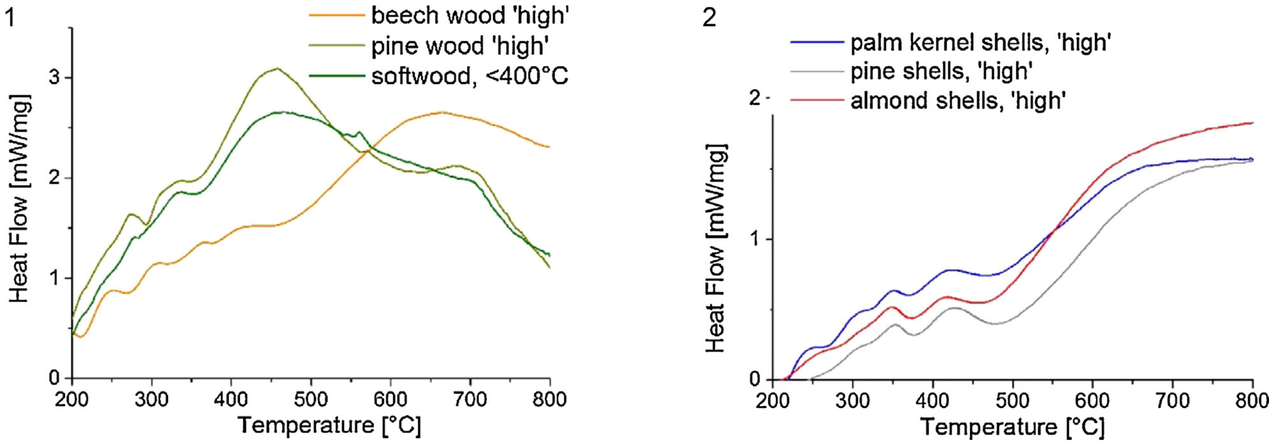

Fig. 13. (1) Heat Flow of woods (High). (2) Heat Flow of shells (High).

It can be stated, that all three shell types are close to their maximum torrefied state. In all cases of shells since their exothermic heat flows are low, especially at torrefaction temperature range (200–350 °C); higher torrefaction temperatures cannot be reached without external source of heat. In the case of wood, especially softwood, higher torrefaction temperatures may lower the efficiency of the autothermic process, but should be considered in order to increase gasification effectivity.

6. Conclusions

This study describes the influence of the torrefaction process on different organic materials. Surface characteristics, ultimate and proximate analysis and pyrolysis behavior as a result of the previous torrefaction process were described and discussed. The results can be summarized as follows:

- The torrefaction process lowers the amount of oxygen of biomass significantly, when carried out at high temperatures of around 300 °C.
- The values of the ultimate and proximate analysis depend strongly on the origin of the organic material. The specific increase of the heating value is ~2 MJ/kg for wooden material and up to 4 MJ/kg for the investigated shell types.
- The element concentrations and especially the amount of volatiles after torrefaction process are unique for the type of biomass: wooden biomass or organic shells. It is not possible to achieve similar characteristics of proximate analysis (of nut shells) by increasing the torrefaction temperature of wooden biomass. So every type of biomass must be treated in a special way in order to match the specific requirements for gasification and therefore the gasification characteristics for each biomass type must be unique. This implication is under further investigation at the department for Ferrous Metallurgy, RWTH Aachen University.
- The BET method showed slightly lower surface areas (around 30% lower) for high torrefied biomass than for pulverized fossil coal.
- The development of porous structure through a torrefaction process is different for wooden biomass and shells in general. The fine porous structure of shells is developing at high torrefaction temperatures, whereas wooden biomass develops a coarse structure at those conditions.
- For high torrefied material, wood or shells, the final weight loss at 800 °C was close to the initial amount of volatile matter. That did not occur to pyrolyzed softwood (prepyrolysed at up to 400 °C).
- The massive weight loss stopped for pyrolyzed wood at a similar level than for the different shells, whereas the final loss was significantly higher than the initial amount of volatile mass. This indicates, that there were frozen polymerization reactions from the previous heat treatment, so there was no activation energy required to initialize these reactions. The degradation of mass may be improved due to the quick reactivation of frozen radicals. These radicals may influence kinetics of fast gasification in a positive way, since these radicals must not be initialized.
- The maximum heat flow during pyrolysis is indicated at lower temperatures for wooden biomass than for all three shell types.
- There might be some potential for higher torrefaction temperatures for wooden biomass, because of the exothermic heat flows during further pyrolysis.
- For all three shell types the maximum torrefaction temperature was close to the investigated state. It can be stated, that the achievable state of shell types through torrefaction process is approximately around 300 °C.

Each investigated biomass shows a unique development in ultimate and proximate analysis during torrefaction temperature range, which cannot achieved by varying the torrefaction conditions for other biomasses. Therefore, the torrefaction process must be adopted to each biomass in order to balance the requirements for an autothermic process mode and the modifications of the proximate and ultimate analysis parameters. For effective gasification, a combination of fast reaction kinetics, supported by non-reformed molecular structure, and high specific heat values must be achieved by the torrefaction process. As the result of these conclusions, there might exist an optimized operating point unique for each biomass, but similar to each biomass type (softwood, hardwood or shells) to generate a product suitable for fast gasification purposes.

Further investigations concerning the potential of the torrefaction process on the fast gasification properties of torrefied biomass will be carried out.

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